Widespread global increase in intense lake phytoplankton blooms since the 1980s

https://doi.org/10.1038/s41586-019-1648-7

Received: 11 January 2018

Accepted: 6 August 2019

Jeff C. Ho[1,2]*, Anna M. Michalak[1]* & Nima Pahlevan[3,4]

Freshwater blooms of phytoplankton affect public health and ecosystem services globally[1,2]. Harmful effects of such blooms occur when the intensity of a bloom is too high, or when toxin-producing phytoplankton species are present. Freshwater blooms result in economic losses of more than US$4 billion annually in the United States alone, primarily from harm to aquatic food production, recreation and tourism, and drinking-water supplies[3]. Studies that document bloom conditions in lakes have either focused only on individual or regional subsets of lakes[4–6], or have been limited by a lack of long-term observations[7–9]. Here we use three decades of high-resolution Landsat 5 satellite imagery to investigate long-term trends in intense summertime near-surface phytoplankton blooms for 71 large lakes globally. We find that peak summertime bloom intensity has increased in most (68 per cent) of the lakes studied, revealing a global exacerbation of bloom conditions. Lakes that have experienced a significant ($P < 0.1$) decrease in bloom intensity are rare (8 per cent). The reason behind the increase in phytoplankton bloom intensity remains unclear, however, as temporal trends do not track consistently with temperature, precipitation, fertilizer-use trends or other previously hypothesized drivers. We do find, however, that lakes with a decrease in bloom intensity warmed less compared to other lakes, suggesting that lake warming may already be counteracting management efforts to ameliorate eutrophication[10,11]. Our findings support calls for water quality management efforts to better account for the interactions between climate change and local hydrological conditions[12,13].

The reported incidence of toxic phytoplankton blooms has risen considerably over the past half-century[14]. While it is generally understood that nutrient loading drives phytoplankton blooms[15], the degree to which bloom conditions are changing globally and the factors that drive these changes among multiple interacting stressors[16] are still uncertain[17]. An understanding of global patterns, trends and drivers is necessary, however, for designing effective management and remediation strategies[18]. Whereas past studies synthesizing information on the long-term trends in phytoplankton blooms of lakes have been limited by data availability, recent advances in cloud-based parallel computing have made it possible to leverage high-resolution freely accessible satellite imagery over large areas, enabling the study of long-term environmental trends on a global scale[19,20].

Here, we take advantage of these advances to generate a long-term record of intense, near-surface phytoplankton blooms for dozens of large lakes across the globe. We use data from the Landsat 5 satellite to generate time series of peak summer bloom intensity from 1984 to 2012 for 71 lakes in 33 countries across 6 continents (Fig. 1). In total, the data span 30,922 scenes and 72.6 billion lake pixels. The study lakes span a broad range of physical characteristics and degree of anthropogenic impacts (Supplementary Table 1; see Methods for a full description of the implemented approach). Seasonal peak bloom intensity for a given lake and year is defined based on the maximum observed lake-wide near-infrared signal magnitude, with a first-order correction of atmospheric interference using the shortwave-infrared signal[21]. Remotely sensed observations within the near-infrared part of the electromagnetic spectrum are sensitive to intense, near-surface algal blooms (see Methods). An initial superset of 154 lakes was selected based on their inclusion in previous studies that leveraged remote sensing by satellites[22,23], thus reducing the likelihood that persistent cloudiness obscured the images. These lakes all have surface areas of more than 100 km^2; globally, lakes within this size range contain approximately 95% of all water stored in lakes[24]. Data of lakes for which little signal was observed throughout the study period, as well as data of lakes for which the signal was far outside the range over which the original algorithm was designed[21], were removed. A smaller number of additional lakes were removed due to previously documented evidence of a lack of phytoplankton blooms. Of the final selected lakes, 38 have a documented presence of harmful cyanobacterial species, while the rest show evidence of other phytoplankton species (10 lakes) or no reported evidence of blooms (23 lakes). Given the heterogeneity in lake characteristics, the time series of the interannual bloom intensity for each lake is normalized by its own long-term mean and s.d. to assess the relative change in bloom intensity over time. This approach eliminates the need to compare absolute

---

[1]Department of Global Ecology, Carnegie Institution for Science, Stanford, CA, USA. [2]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA. [3]NASA Goddard Space Flight Center, Greenbelt, MD, USA. [4]Science Systems and Applications Inc, Lanham, MD, USA. *e-mail: jeffho@stanford.edu; michalak@stanford.edu

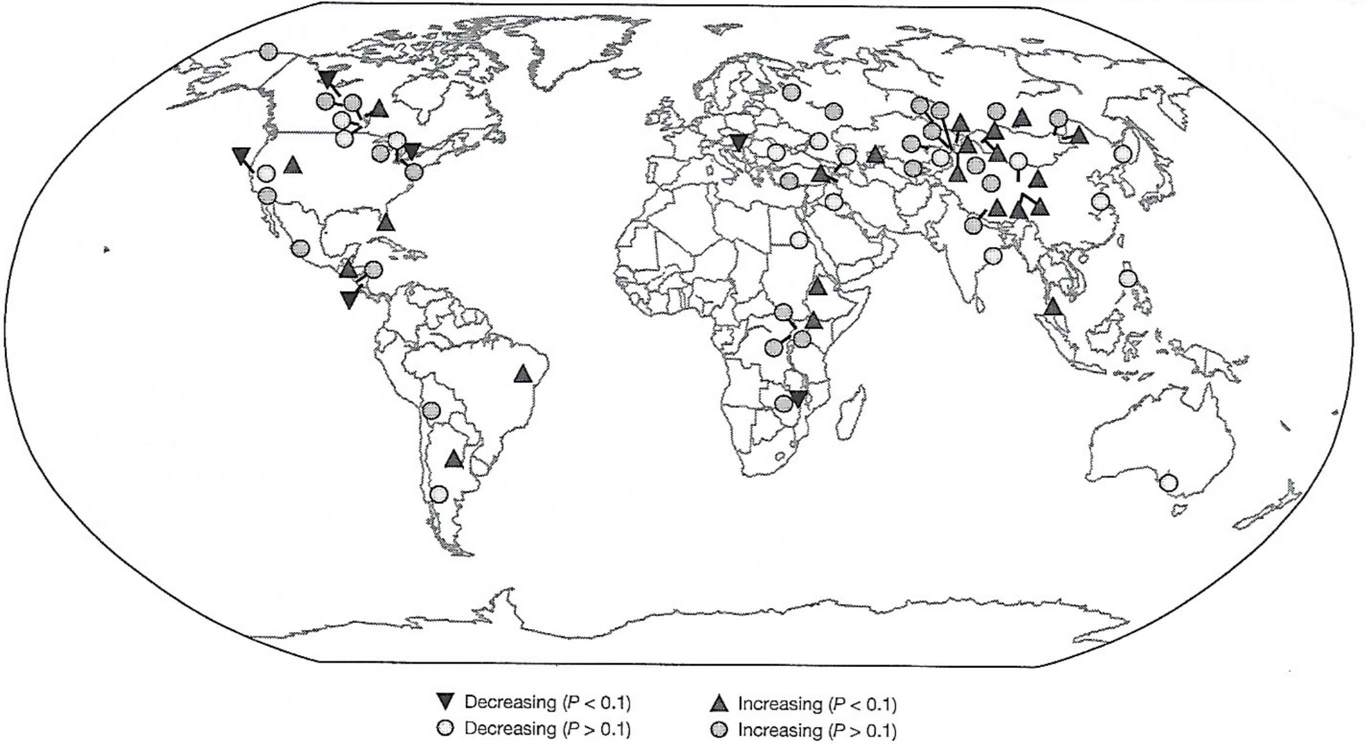

Fig. 1 | Global distribution of lake bloom intensity trends shows that the peak summertime bloom intensity has increased since the 1980s. The map shows bloom intensity trends for all 71 study lakes for the period 1984–2012 (Supplementary Table 1). Colours and symbols indicate whether the bloom intensity decreased (blue) or increased (red), and whether the trend is statistically significant (triangles for $P < 0.1$; circles for $P > 0.1$). The base map was generated using Generic Mapping Tools[33].

magnitudes across lakes, which has been an important barrier to past syntheses across lakes[25].

We find that the implemented algorithm is able to successfully capture previously documented spatial gradients in the severity of phytoplankton blooms within individual lakes and temporal trends in phytoplankton bloom intensity for specific lakes (Extended Data Fig. 1 and Methods). Using simulations of atmospheric radiative transfer, we also find that the algorithm is insensitive to reported variations in Landsat 5 orbit or image radiometric quality, primarily owing to the strong signal that arises from the intense, near-surface blooms identified in study lakes (see Supplementary Information). These results suggest that a single algorithm can indeed identify intense phytoplankton blooms despite the large differences in optical properties across lakes[26], as long as the focus is on interannual rather than interlake variability. This lends support to the approach implemented in this study for tracking long-term trends globally. We then used all 71 study lakes to assess global trends in summertime peak phytoplankton bloom intensity. We also used a subset of 49 lakes with at least 14 years of data to explore more detailed historical temporal patterns in phytoplankton bloom conditions, for which the 14-year threshold was selected on the basis of previously published studies on global lake temperatures[22,27].

We find that peak summertime phytoplankton bloom intensity has increased in more than two-thirds of study lakes since the 1980s (48 out of 71 lakes) (Fig. 1). Increases in bloom intensity are statistically significant for close to a third of all lakes ($P < 0.1$ for 22 out of 71 lakes), whereas only 6 lakes exhibited a statistically significant decrease in intensity ($P < 0.1$). A similar proportion of lakes has an increasing bloom intensity among those with a documented presence of cyanobacteria (24 out of 38 lakes) compared to lakes without cyanobacteria (24 out of 33 lakes), and the proportion of lakes with increases in bloom intensity is also consistent across lakes with different areas, volumes, mean and maximum depths, and latitudes (see Supplementary Table 1 and Supplementary Information). These results suggest that the observed trends are widespread globally and across lake types, in contrast to previous hypotheses of differential impacts as a function of latitude[28] or morphometry[29]. This finding provides a global perspective that is consistent with surveys of sedimentary records across temperate–subarctic lakes[6] that show sharp increases in the concentrations of cyanobacterial pigments after 1985. This finding also corroborates putative trends of increasing harmful cyanobacterial blooms globally[17], and counters the hypothesis that increased reporting of toxic blooms is instead a by-product of increased scientific attention[30].

We find that lake phytoplankton bloom histories follow one of four prototypical pathways, termed here 'sustained improvement', 'improvement then deterioration', 'deterioration' and 'no significant trend' (Fig. 2a–d and Methods). The two pathways that include deteriorating conditions reveal that increases in peak bloom intensity occurred predominantly in the latter half of the study period (Fig. 2b, c). For example, three-quarters of study lakes (51 out of 68) with sufficient data for the second half of the study period (1998–2012) exhibited an increase in bloom intensity during this period, whereas only a third (22 out of 66) experienced an increase during the first half (1984–1997). The reason behind the temporal coherence of changes in phytoplankton bloom intensity remains unclear, as temporal trends do not track consistently with temperature, precipitation, fertilizer-use trends, satellite data availability or geomorphological characteristics of individual lakes (Extended Data Figs. 2–5 and Supplementary Information), nor are there widespread trends in the seasonal timing of peak bloom intensity (see Supplementary Information).

We find that although lakes that exhibited sustained improvement were rare ($n = 6$), they experienced less warming (or more cooling) relative to those that exhibited improvement then deterioration ($P = 0.09$; Fig. 3 and Extended Data Fig. 6), suggesting that lake warming may have counteracted management efforts in the latter group. This finding suggests that nutrient reduction targets based on historical relationships

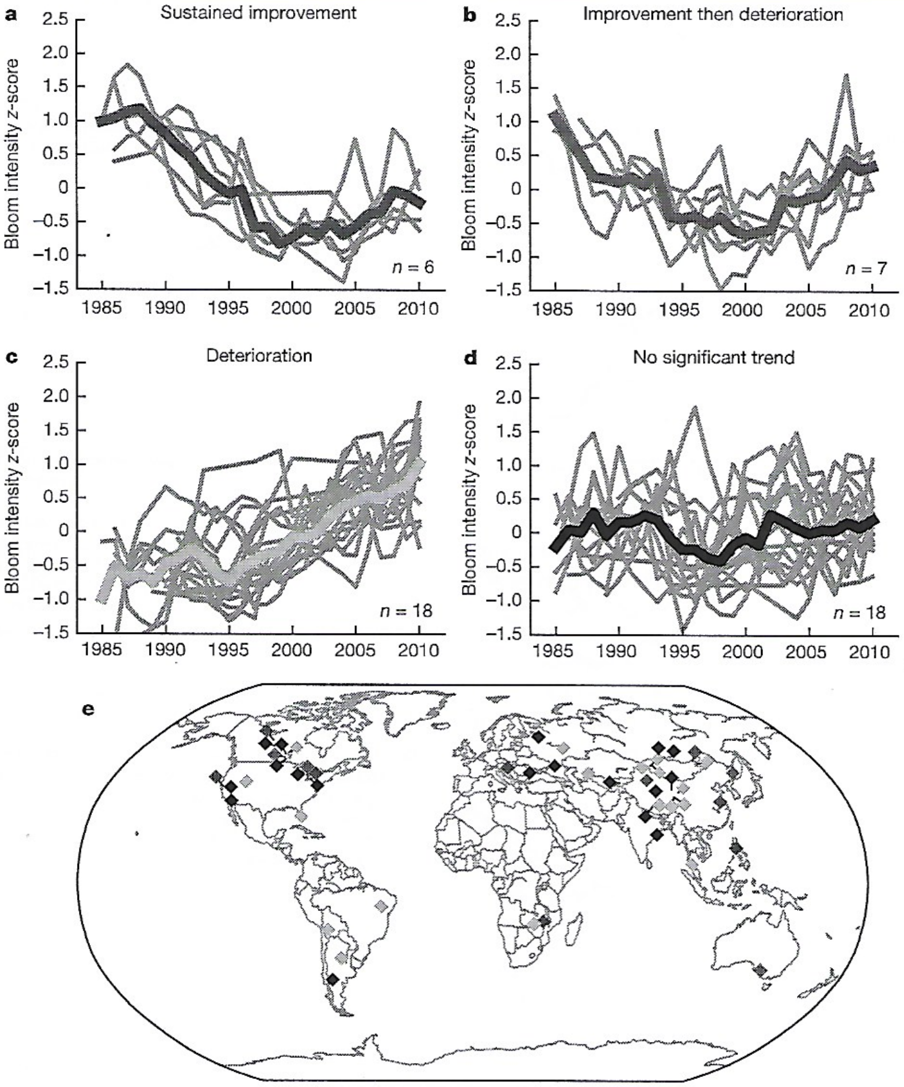

Fig. 2 | Lake bloom histories follow one of four prototypical pathways. **a–d**, Time series for lakes with at least 14 years of data ($n=49$) categorized by historical pathway. Grey lines show 5-year moving averages of normalized bloom intensity, with coloured lines showing pathway averages across lakes. The time series of the bloom intensity *z*-score for each lake is calculated using its own historical mean and s.d. **e**, Global distribution of lake pathways. The base map was generated using Generic Mapping Tools[33].

between bloom severity and nutrient loading may have to be revised in the context of climate change, as has been hypothesized[11]. Generalizing the impact of warming across a wide range of lakes is inadvisable, however, as trends across the full lake ensemble showed little direct correlation with temperature (Fig. 4, Extended Data Figs. 2, 3 and Supplementary Information). Rather, these findings suggest that the effects of global lake warming differ depending on lake-specific characteristics[31], and highlight the importance of assessing the role of lake attributes in modulating the impact of temperature on nutrient–phytoplankton relationships[32].

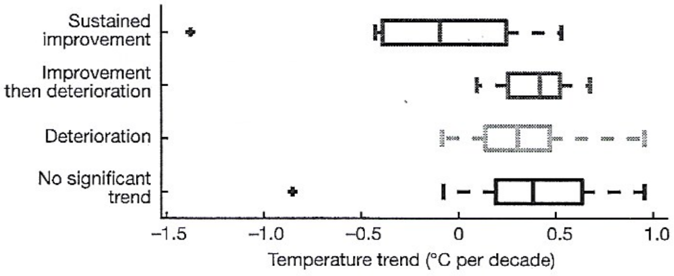

Fig. 3 | Lakes that experienced improvements in bloom conditions tend to have experienced little to no warming. Box plots of the water temperature trend (1985–2012) binned by lake historical pathway. Each box extends from the first to the third quartile values, with a line at the median. The whiskers extend to 1.5× the interquartile range from the edges of the box. The plus symbols show outlier values past the end of the whiskers.

Overall, this study provides a global view of trends in intense lacustrine near-surface phytoplankton blooms over the past three decades. We examine bloom histories for lakes with widely differing characteristics and geographical locations, and demonstrate the promise of long-term satellite observations for tracking intense bloom conditions across a heterogeneous set of systems to augment geographically and temporally limited in situ monitoring efforts. Our results corroborate the putative reported increase in bloom occurrence and intensity globally, and highlight that lakes that have exhibited a long-term decrease in bloom intensity are rare. Results further show that sustained decreases in bloom intensity are more likely to have occurred in lakes with little or no warming, suggesting that rising lake temperatures may hamper environmental recovery, and illustrating the importance of identifying factors that make some lakes more susceptible to the effects of warming.

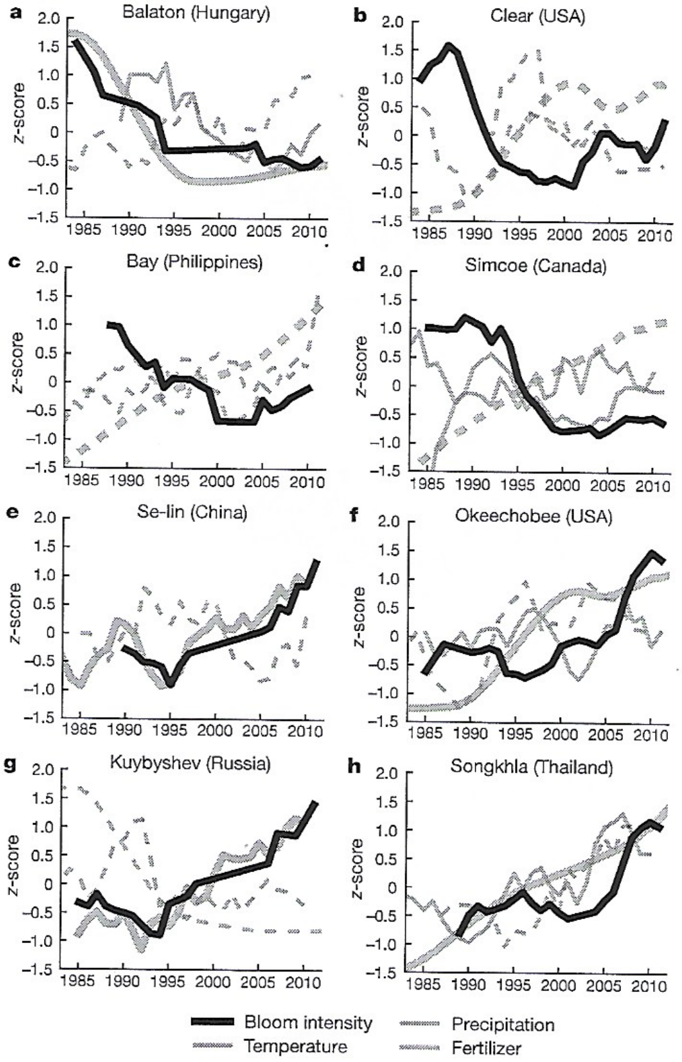

Fig. 4 | Lake bloom histories show no consistent correspondence with temperature, precipitation and fertilizer use. a–h, Five-year moving averages of normalized near-surface bloom intensity, summer lake temperatures, and total precipitation and fertilizer application rate over the watershed for eight prototypical lakes. **a–d**, Lakes follow the sustained improvement pathway. **e–h**, Lakes follow the deterioration pathway. Thicker temperature, precipitation and fertilizer lines indicate that the Pearson correlation coefficient with bloom intensity is significant ($P < 0.1$). Dashed lines indicate anti-correlations.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-019-1648-7.

1. Pick, F. R. Blooming algae: a Canadian perspective on the rise of toxic cyanobacteria. *Can. J. Fish. Aquat. Sci.* **73**, 1149–1158 (2016).
2. Ndlela, L. L., Oberholster, P. J., Van Wyk, J. H. & Cheng, P. H. An overview of cyanobacterial bloom occurrences and research in Africa over the last decade. *Harmful Algae* **60**, 11–26 (2016).
3. Kudela, R. M. et al. *Harmful Algal Blooms. A Scientific Summary For Policy Makers* (IOC/UNESCO, 2015).
4. Hampton, S. E. et al. Sixty years of environmental change in the world's largest freshwater lake – Lake Baikal, Siberia. *Glob. Change Biol.* **14**, 1947–1958 (2008).
5. Duan, H. et al. Two-decade reconstruction of algal blooms in China's Lake Taihu. *Environ. Sci. Technol.* **43**, 3522–3528 (2009).
6. Taranu, Z. E. et al. Acceleration of cyanobacterial dominance in north temperate-subarctic lakes during the Anthropocene. *Ecol. Lett.* **18**, 375–384 (2015).
7. Carvalho, L. et al. Sustaining recreational quality of European lakes: minimizing the health risks from algal blooms through phosphorus control. *J. Appl. Ecol.* **50**, 315–323 (2013).
8. Beaulieu, M., Pick, F. & Gregory-Eaves, I. Nutrients and water temperature are significant predictors of cyanobacterial biomass in a 1147 lakes data set. *Limnol. Oceanogr.* **58**, 1736–1746 (2013).
9. Kosten, S. et al. Warmer climates boost cyanobacterial dominance in shallow lakes. *Glob. Change Biol.* **18**, 118–126 (2012).
10. Posch, T., Köster, O., Salcher, M. M. & Pernthaler, J. Harmful filamentous cyanobacteria favoured by reduced water turnover with lake warming. *Nat. Clim. Change* **2**, 809–813 (2012).
11. Paerl, H. W. et al. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae* **54**, 213–222 (2016).
12. Winder, M. Lake warming mimics fertilization. *Nat. Clim. Change* **2**, 771–772 (2012).
13. Paerl, H. W. & Huisman, J. Blooms like it hot. *Science* **320**, 57–58 (2008).
14. Carmichael, W. in *Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs* (ed. Hudnell, H. K.) 105–125 (Springer-Verlag, 2008).
15. Schindler, D. W., Carpenter, S. R., Chapra, S. C., Hecky, R. E. & Orihel, D. M. Reducing phosphorus to curb lake eutrophication is a success. *Environ. Sci. Technol.* **50**, 8923–8929 (2016).
16. Winter, J. G., Young, J. D., Landre, A., Stainsby, E. & Jarjanazi, H. Changes in phytoplankton community composition of Lake Simcoe from 1980 to 2007 and relationships with multiple stressors. *J. Great Lakes Res.* **37**, 63–71 (2011).
17. Huisman, J. et al. Cyanobacterial blooms. *Nat. Rev. Microbiol.* **16**, 471–483 (2018).
18. McCrackin, M. L., Jones, H. P., Jones, P. C. & Moreno-Mateos, D. Recovery of lakes and coastal marine ecosystems from eutrophication: a global meta-analysis. *Limnol. Oceanogr.* **62**, 507–518 (2017).
19. Gorelick, N. et al. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **202**, 18–27 (2017).
20. Zhu, Z. et al. Benefits of the free and open Landsat data policy. *Remote Sens. Environ.* **224**, 382–385 (2019).
21. Ho, J. C., Stumpf, R. P., Bridgeman, T. B. & Michalak, A. M. Using Landsat to extend the historical record of lacustrine phytoplankton blooms: a Lake Erie case study. *Remote Sens. Environ.* **191**, 273–285 (2017).
22. Schneider, P. & Hook, S. J. Space observations of inland water bodies show rapid surface warming since 1985. *Geophys. Res. Lett.* **37**, L22405 (2010).
23. Sharma, S. et al. A global database of lake surface temperatures collected by in situ and satellite methods from 1985–2009. *Sci. Data* **2**, 150008 (2015).
24. Messager, M. L., Lehner, B., Grill, G., Nedeva, I. & Schmitt, O. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nat. Commun.* **7**, 13603 (2016).
25. Hampton, S. E. Understanding lakes near and far. *Science* **342**, 815–816 (2013).
26. Spyrakos, E. et al. Optical types of inland and coastal waters. *Limnol. Oceanogr.* **63**, 846–870 (2018).
27. O'Reilly, C. M. et al. Rapid and highly variable warming of lake surface waters around the globe. *Geophys. Res. Lett.* **42**, 10,773–10,781 (2015).
28. Downing, J. in *Global Environmental Change* (ed. Freedman, B.) 221–229 (Springer, 2014).
29. Kraemer, B. M. et al. Morphometry and average temperature affect lake stratification responses to climate change. *Geophys. Res. Lett.* **42**, 4,981–4,988 (2015).
30. Fristachi, A. et al. in *Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs* (ed. Hudnell, H. K.) 45–103 (Springer-Verlag, 2008).
31. Adrian, R. et al. Lakes as sentinels of climate change. *Limnol. Oceanogr.* **54**, 2,283–2,297 (2009).
32. Rigosi, A., Carey, C. C., Ibelings, B. W. & Brookes, J. D. The interaction between climate warming and eutrophication to promote cyanobacteria is dependent on trophic state and varies among taxa. *Limnol. Oceanogr.* **59**, 99–114 (2014).
33. Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J. & Wobbe, F. Generic Mapping Tools: improved version released. *Eos* **94**, 409–410 (2013).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.